Exploring Sterile Neutrinos with IceCube/Deep Core

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Work in progress with grad students Dave Hollander, Warren Wright

Dave Hollander, arXiv:1301.5313

“Anomalies”

more complete description in Bill Louis’ talk

New physics beyond three-flavors?

- LSND
- MiniBooNE
- Reactor anomaly
- Gallium anomaly
- Solar neutrino spectrum
- Cosmology?

“Anomalies”

New physics beyond three-flavors?

- New interactions?
- New “flavors”?

- Each anomaly separately might not be convincing
- If interpreted as 2 flavor oscillations all point to $\sim eV^2$ mass scale
- Need independent tests under different conditions to differentiate

  - correct framework
  - correct parameter space

Sterile neutrinos

- How many?
  - models vs. phenomenological approach

- 3+1: 6 angles

  + lots of phases

- 3+2: 10 angles

- In a given experiment/set of experiments: sensitive to only a subset
  - good: you can keep track of smaller number of parameters
  - not so good: independent tests are hard,
    often probe different parameter space

Sterile neutrinos

- eV^2 mass scale in oscillations:

$$P(\nu_\alpha \to \nu_\beta) \sim \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$

- Search at relevant L/E

- IceCube atmospheric neutrinos at $E \sim \text{few } TeV$

Nunokawa, Peres, Zukanovich Funchal; Choubey;
Razzaque, Smirnov, Esmaili; Barger, Gao, Marfatia

- Issue: IceCube most sensitive to muon tracks
  - one additional neutrino, one mixing angle with steriles
    (not same in all analysis -> can see model dependence)
  - primarily probing sterile mixing with mu-tau (2-3) sector
    (vs. mu-e sector in anomalies)
  - probing same mass scale and angles of similar size,
    but NOT the same angles - cannot "rule out" anomalies

Sterile neutrinos

- How many?

- general phenomenological fit

  (e. g. J. Kopp, P. A. N. Machado, M. Maltoni and T. Schwetz)

- 3+1: too many tensions in data – not a good fit

  6 angles + 3phases -> 5 + 2 in LBL, 3 + 0 SBL

- 3+2: better fits

  still tensions between appearance and disappearance

  9 angles + 5 phases -> 8 + 4 in LBL, 6 + 2 in SBL

- …
- need more constrained framework to get meaningful tests

3+2 Minimal Model

A. Donini, P. Hernandez, J. Lopez-Pavon, M. Maltoni, T. Schwetz
JHEP 1207 (2012) 161

- Minimal model that fits all data, including anomalies

- 2 right handed Weyl fermions -> need to diagonalize

$$M_N = \begin{pmatrix} 0 & m_Y \\ m_Y^T & m_N \end{pmatrix}, \; M_N = Diag(m_4, m_5)$$

-> one massless neutrino
-> 5x5 unitary mixing matrix can be parameterized in terms of four angles (3 PMNS + one new angle θ_{45}) and three phases
-> single angle θ_{45} contributes to oscillations of both active-active and active-sterile flavors
-> highly constrained

3+2 Minimal Model

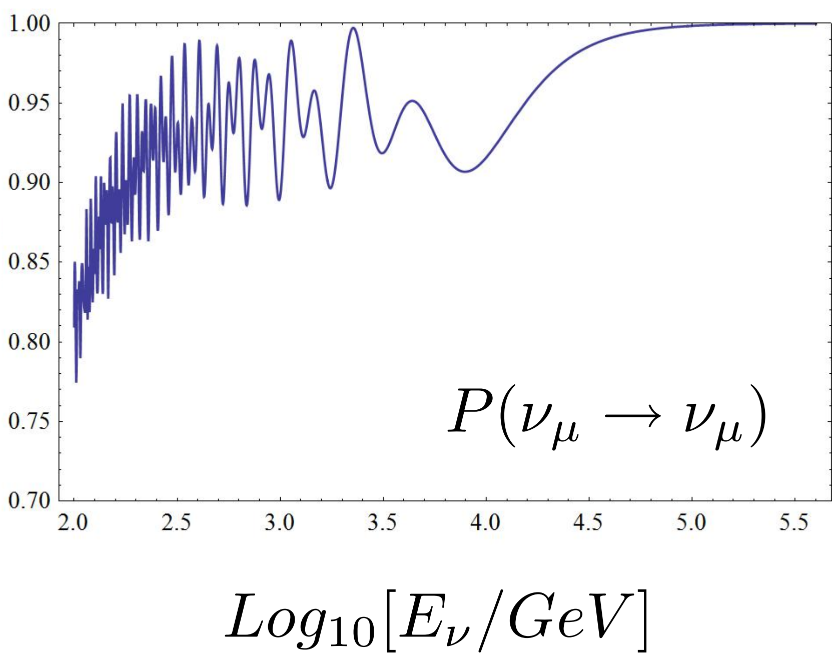
Best fit in 3+2 minimal model:

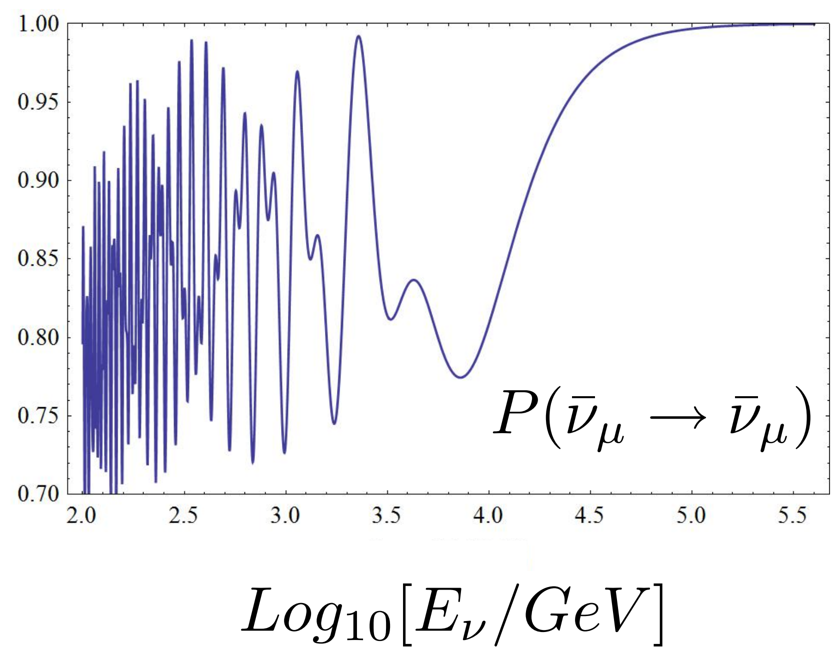
NH

$$|U_{e4}| = 0.149,\ |U_{e5}| = 0.127,\ |U_{\mu 4}| = 0.112,\ |U_{\mu 5}| = 0.127$$

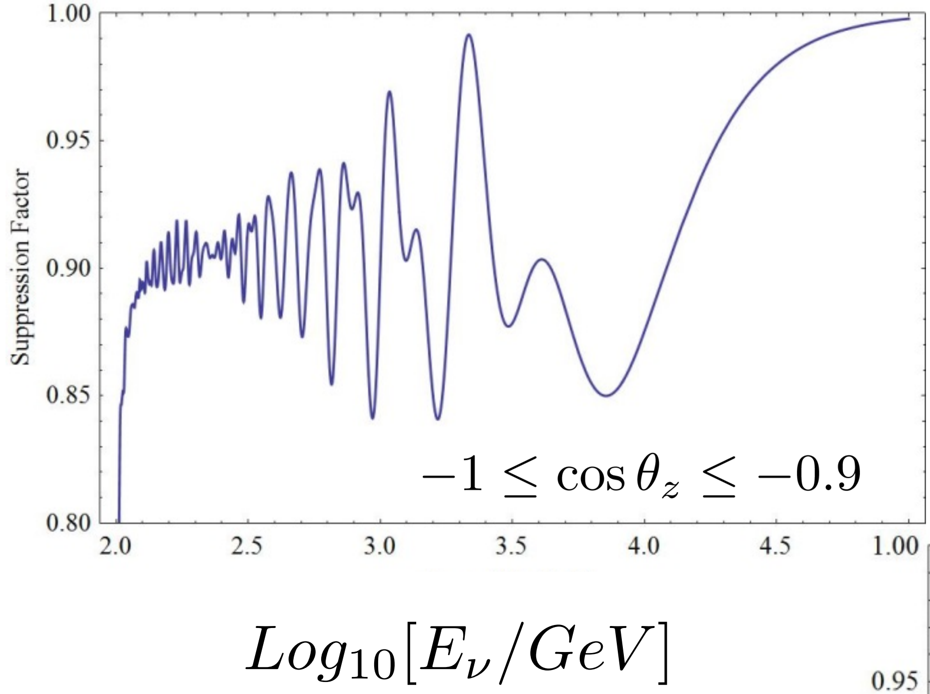
$$\phi_{45} = \mathrm{Arg}(U_{e4}^* U_{e5} U_{\mu 4} U_{\mu 5}^*) = 1.8\pi$$

$$\Delta m_{41}^2 = 0.47 eV^2 \qquad \Delta m_{51}^2 = 0.87 eV^2$$



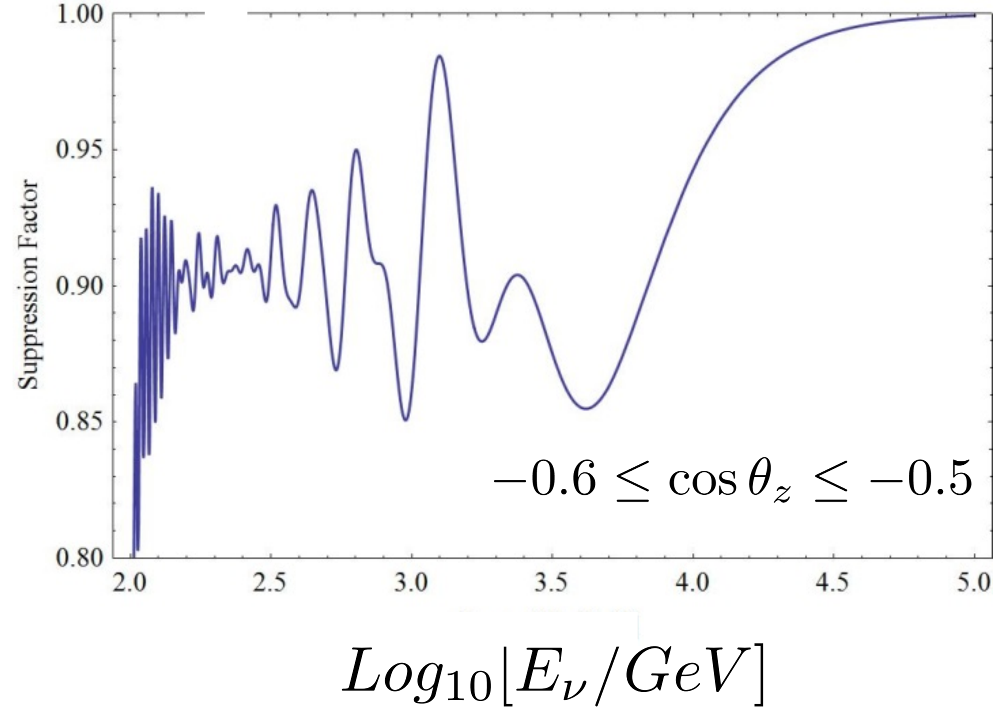


- Compare number of events including oscillations to steriles to number of events with only 3 flavor oscillations



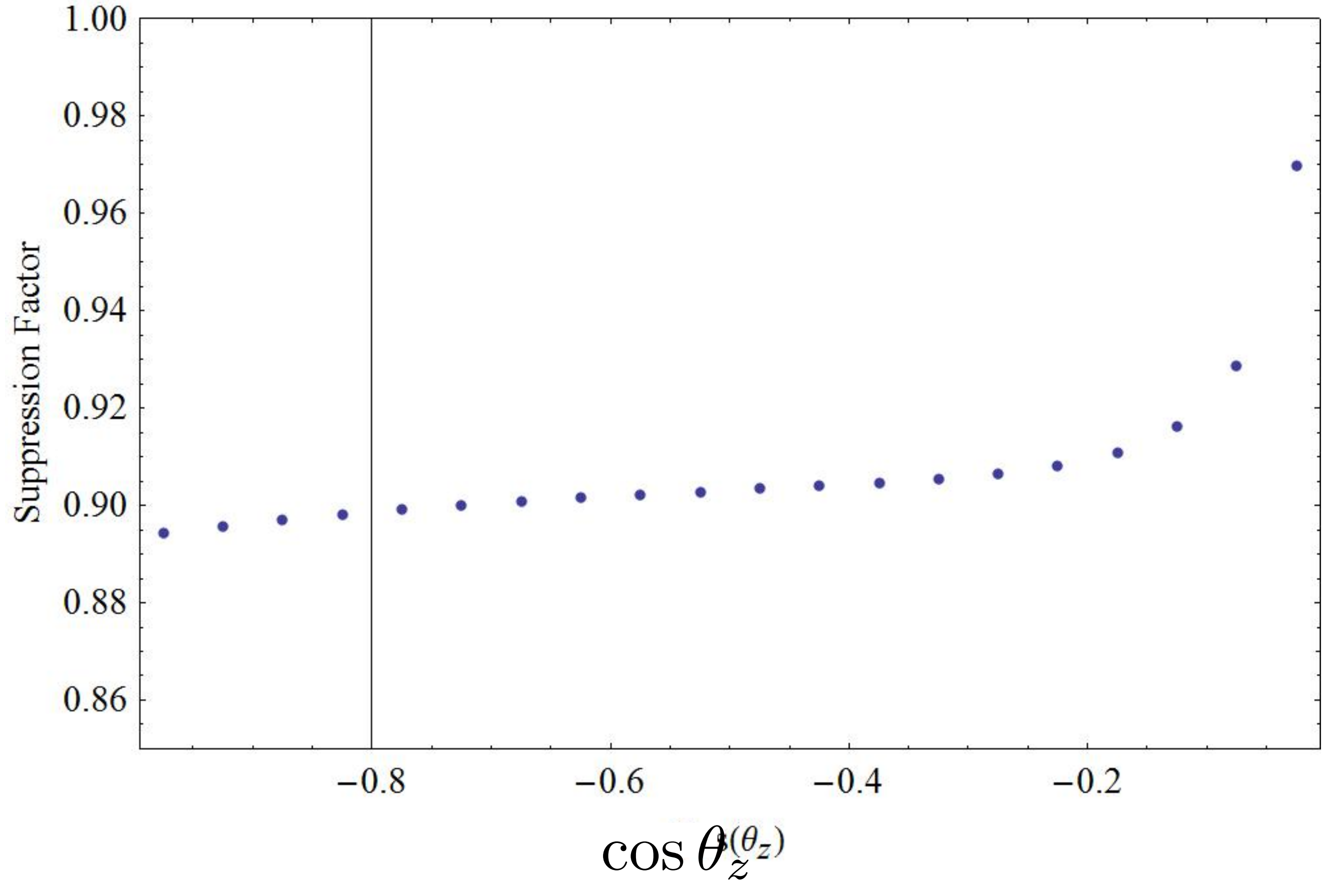
- Get ~15% suppression in certain energy bins

Suppression factors



- Compare number of events including oscillations to steriles to number of events with only 3 flavor oscillations
- Largest contribution in near vertical bins
- Lose information when integrating over energies

Suppression factors

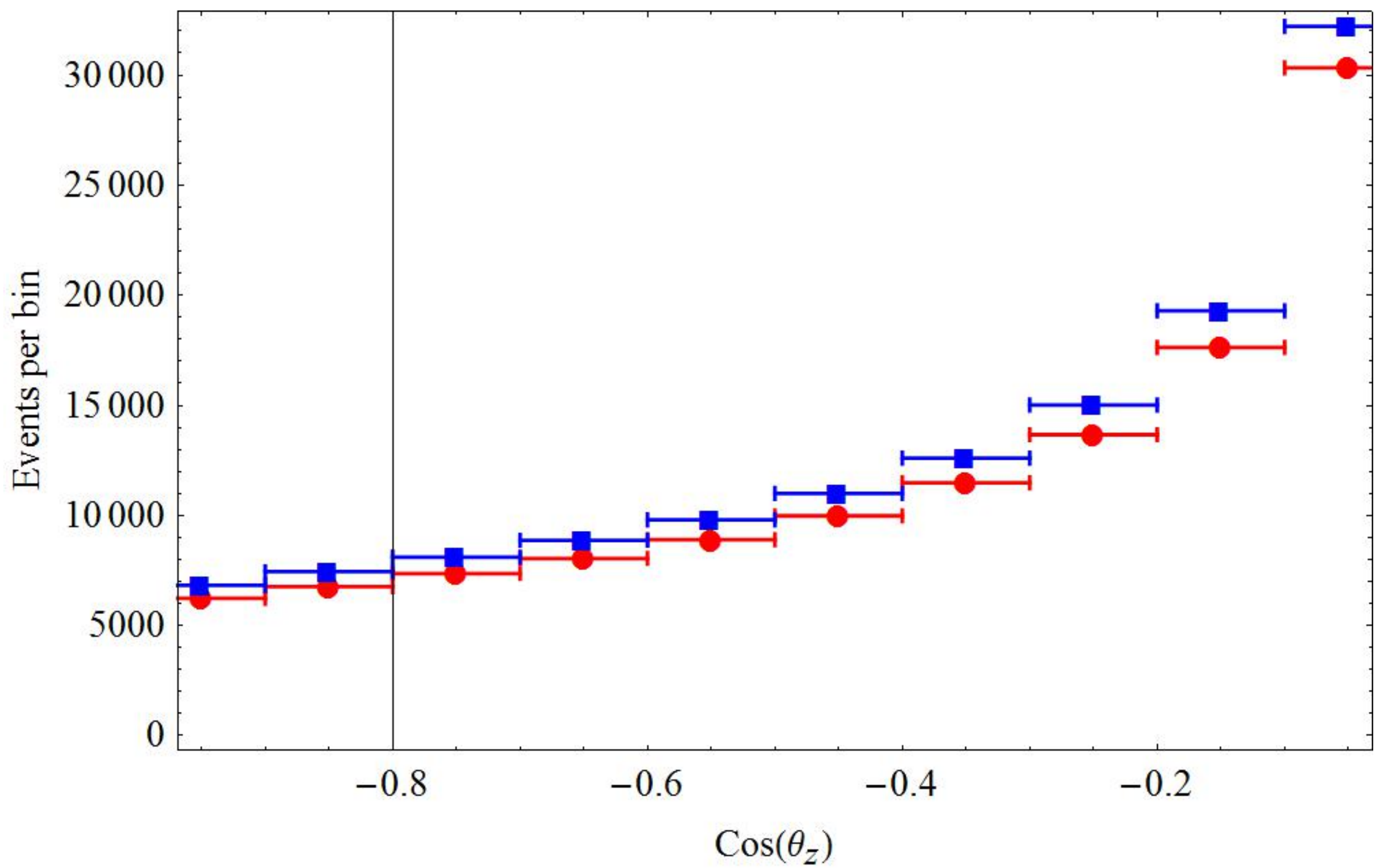


Events in full detector: 3 flavors, 3+2 minimal model

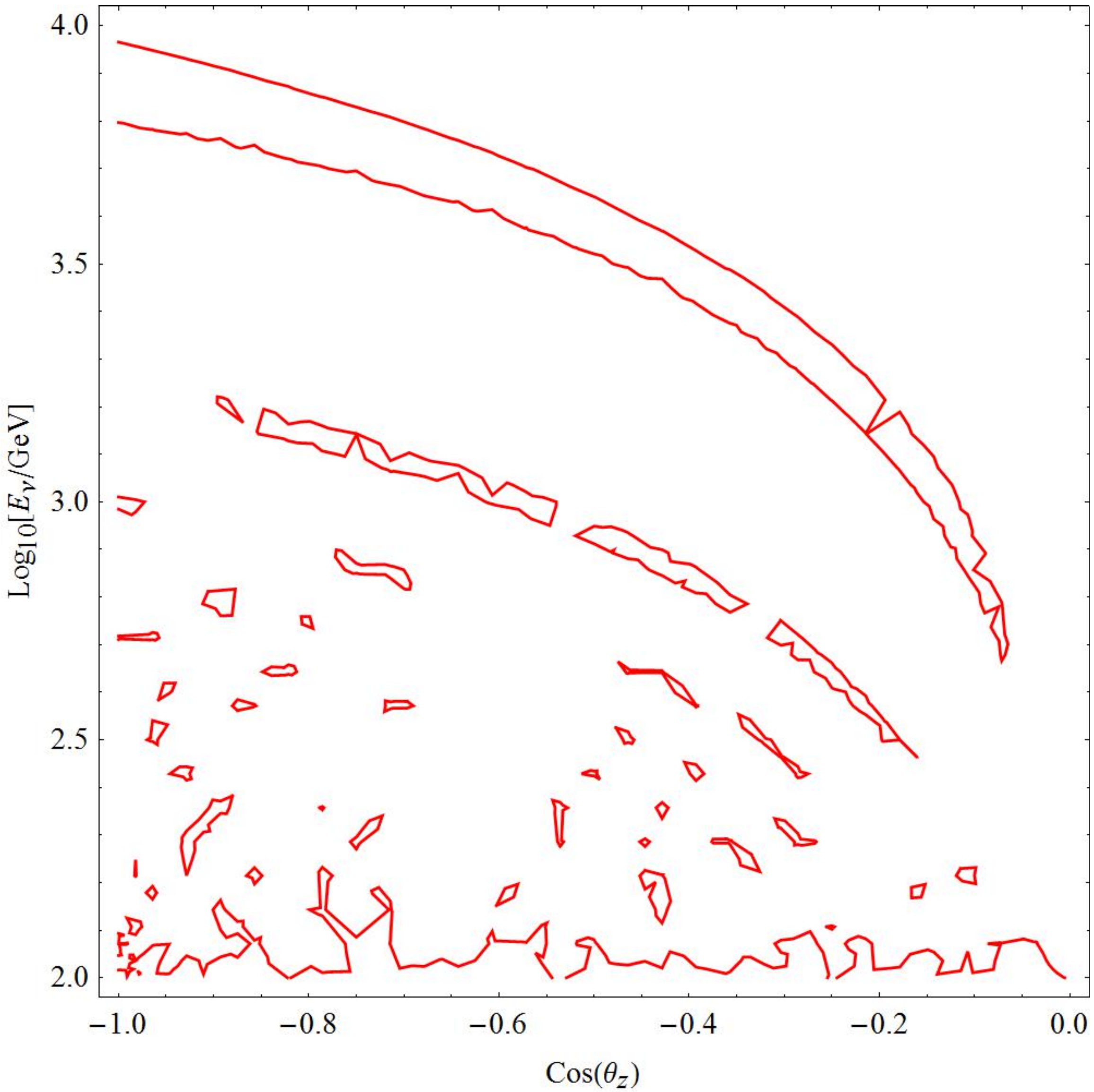
(MC including systematics)

In fit to IC79 including statistical and systematic errors 3+2 minimal model has somewhat better χ^2 value than 3 or 3+1 models

-> not significant at this point due to uncertainties



Energy – zenith angle parameter space where the 3+2 minimal model has a relative effect larger than 14%: likely to be observable given uncertainties



Present: systematic uncertainties are still large

Future: better statistics and understanding of systematics will lead to meaningful sensitivity to sterile neutrino models

Additional tests of 3+2 minimal model

Best fit:

$$|U| = \begin{pmatrix} 0.828 & 0.523 & 0.045 & 0.149 & 0.127 \\ 0.354 & 0.662 & 0.639 & 0.112 & 0.127 \\ 0.435 & 0.462 & 0.510 & 0.374 & 0.313 \\ 0 & 0.209 & 0.362 & 0.905 & 0.081 \\ 0 & 0.177 & 0.315 & 0.081 & 0.929 \end{pmatrix}$$

Large tau/sterile mixing elements

Tau appearance should be large in this model

Tau sensitivity?

very hard in TeV energy range

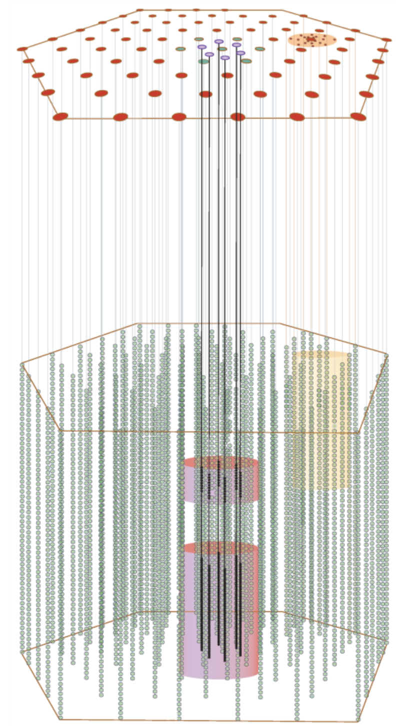
maybe possible at lower or higher energy?

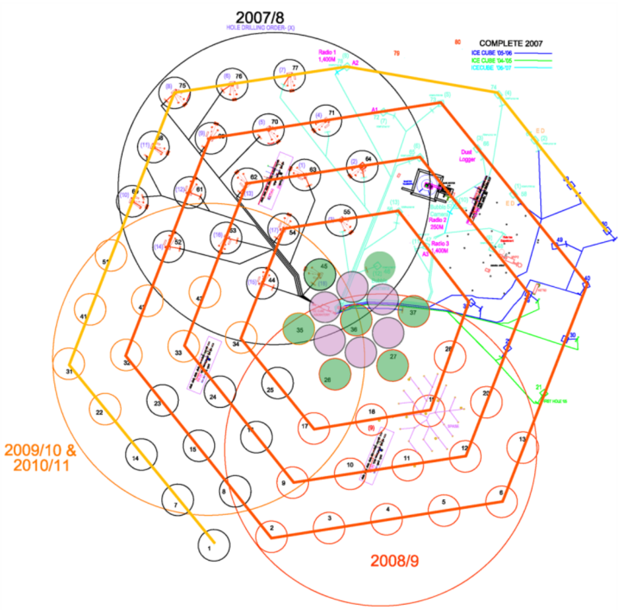
“Low energy” (10-100 GeV)

- for $\Delta m^2 \sim eV^2$ the oscillation signal averages out
- -> small constant correction to oscillation probabilities determined by mixing angles
- looks a lot like NSI – some sensitivities can be extracted from NSI analysis in IceCube Deep Core (Warren Wright’s talk for muon tracks)
- look specifically for tau appearance signal which is large in the the 3+2 minimal model

IceCube Deep Core

- motivation: look for neutrinos from galactic sources, dark matter annihilation
  - galactic center is above horizon at South Pole
  - need to reduce large cosmic muon background
- 4π coverage
  look at down-going events,
  study galactic sources, galactic center





- 6+2 strings, 7m DOM spacing
- low energy threshold: opens the 10 -- 100 GeV neutrino energy range
- overlap with Super-Kamiokande at low energy and with IceCube at high energies

Neutrino oscillations in the IceCube Deep Core

tracks: μ-like fully contained events and cascades:

Angular distribution:

- $\cos\theta \in (0,1)$ atmospheric flux normalization
- $\cos\theta \in (-1,0)$ + main oscillation signal ($\Delta m^2_{32},\ \theta_{23}$)
- $\cos\theta \in (-1,-0.7)$ + matter effects (θ_{13}, hierarchy, CP)

Energy distribution:

- $E \leq 40\,\mathrm{GeV}$: neutrino oscillations
- $50\,\mathrm{GeV} \leq E \leq 5\,\mathrm{TeV}$: atmospheric neutrino flux
- $E \geq 10\,\mathrm{TeV}$: Earth density profile

ICDC physical mass: $15\,\mathrm{Mt}$ $(28\mathrm{Mt})$

Effective mass in our analysis: $1\,\mathrm{Mt} - 12\,\mathrm{Mt}$ (energy dependent)

O. Mena, I. M., S. Razzaque (2008);

G. Giordano, O. Mena, I. M. (2010), E. Fernandez-Martinez, G. Giordano, O. Mena, I. M. (2010)

IceCube Deep Core detector taking data !

- built to look for galactic sources, dark matter annihilation
- atmospheric neutrinos

  high statistics, large energy range, many distances

  > 50,000 events per year

  better understanding the background for other sources
- neutrino oscillations

  highly significant oscillation signal

  good parameter sensitivity

  ν_τ : oscillations, interactions, cascade detection helped by

  - $\Phi_{\nu_\mu} \sim 10\,\Phi_{\nu_e}$
  - oscillations

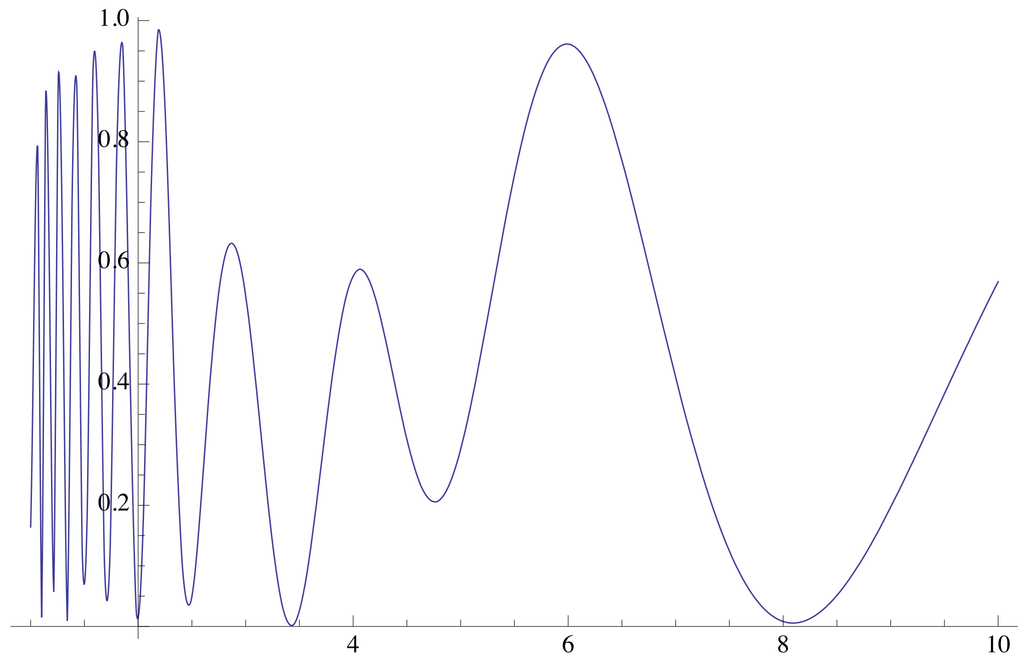
  mass hierarchy

  …

  Use the data we already have and get the most of it!

PINGU

- more physics than ICDC
  lower energy:
  better “shape” of first peak
  (precision)
  secondary peaks ->
  two mass scales contribute
  (CP violation+matter effect)



- analysis more involved than ICDC
  - better reconstruction/resolution
  - atmospheric flux: transition between mu+pi and pi:
    -> flavor and energy dependence
  - cross-sections: many contributions
    -> energy dependent uncertainties
    -> limited use of full kinematics: very useful with DIS in ICDC

  -> larger systematics/more work + outside input potentially very useful (cross section measurements, etc.)

What physics?

- Input θ_{13} from reactors, etc.
- Precision measurement of main oscillation parameters
- Above 10 GeV – nu tau cascades
- Matter effects – hierarchy
- few GeV – interference of two mass scales – CP phase
- theta_23 octant
- non-standard interactions – matter effects
- very useful information in combination with long baseline exp.

What is needed:

- (Some) angular reconstruction: 3-4 bins sufficient
- Energy measurement: important to have few GeV and > 10GeV
- Flavor ID?

Astrophysical Neutrinos (arXiv:1301.5313)

David Hollander

- Examine energy dependent flavor ratios from astrophysical sources (GRB, AGN)
- Flavor ratios depend on the cooling mechanism at the source
  - Can we learn about the source properties by measuring flavor ratios?
- Measuring the flavor ratios can also potentially tell us whether we have sterile neutrino oscillations
- Neutrinos from

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) \rightarrow e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_{\mu}(\nu_{\mu}) + \nu_{\mu}(\bar{\nu}_{\mu})$$

produced by γp or $p - \mathrm{nucleon}$ interactions

$$\Phi^d_{\nu_\alpha}(E_\nu) = \sum P_{\alpha\beta}\Phi^s_{\nu_\beta}(E_\nu)$$

Probabilities and Source Fluxes

- Astrophysical sources, very long propagation length
- Probabilities take on average value due to rapid oscillations

$$L/E \gg 1$$

$$P_{\alpha\beta} = \langle P_{\alpha\beta}(L/E) \rangle = \delta_{\alpha\beta} - 2\sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U^*_{\beta j} U_{\alpha j}) = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

- Charged leptons and pions at the source are subject to cooling effects before they decay
  - Cooling mechanisms: synchrotron radiation, adiabatic expansions of the charged plasma

- Suppose energy dependences on pion spectrum and losses

$$\Phi_\pi \propto E^{-2} \qquad\qquad \frac{dE_x}{dt} \propto E_x^n$$

- n = 1 (adiabatic), n = 2 (synchrotron)

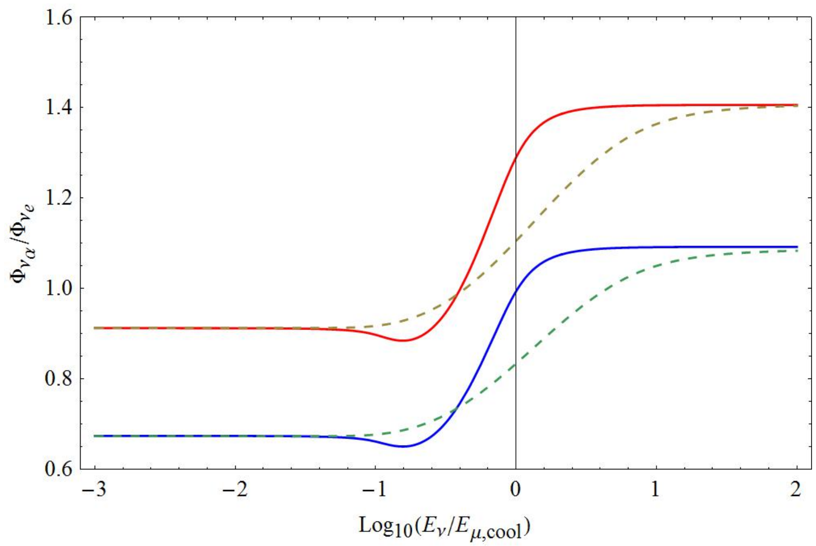
$$\Phi^s_{\nu_\mu}(E_\nu) = -\partial_{E_\nu} \int_{4E_\nu}^{\infty} dE_i \Phi_\pi(E_i) P(E_i, 4E_\nu)$$

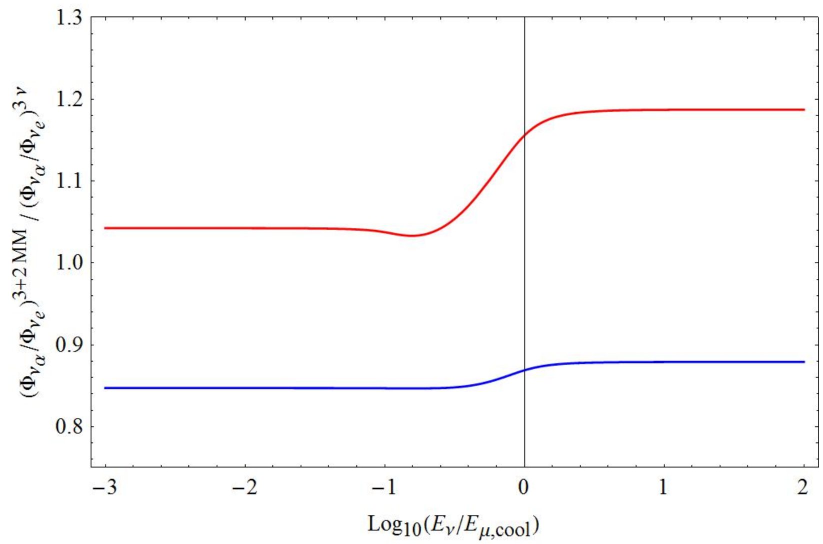
$$\Phi^s_{\nu_\mu}(E_\nu) = \partial_{E_\nu} \int_{3E_\nu}^{\infty} dE_\mu \int_{\frac{4}{3}E_\mu}^{\infty} dE_i \Phi_\pi(E_i) P(E_\mu, 3E_\nu) \partial_{E_\mu} P(E_i, \frac{4}{3}E_\mu)$$

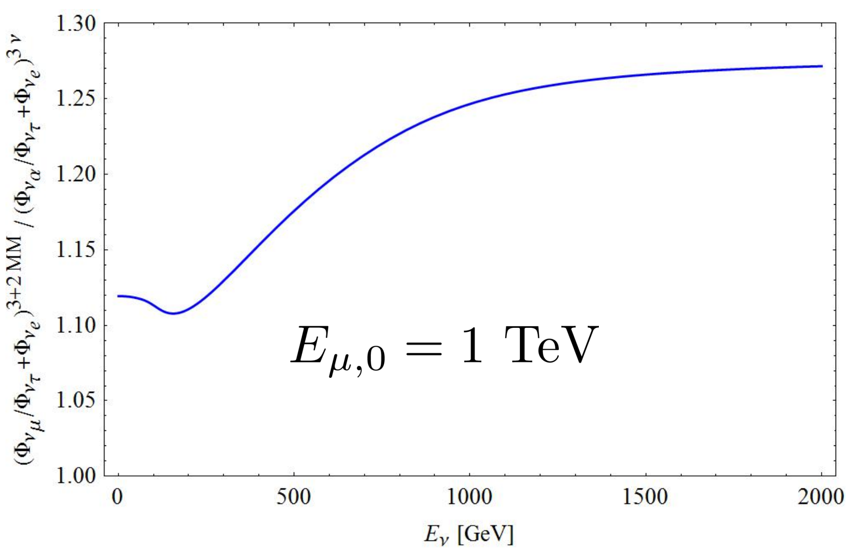
$$P(E_i, E_f) = 1 - Exp[-E_0^n (E_f^{-n} - E_i^{-n})/n]$$

- The cooling energy contains information about the source, such as magnetic field strength
  - Can be extracted from measurements of flavor ratios

Results


$\Phi_{\nu_\alpha}/\Phi_{\nu_e}$
$\mathrm{Log}_{10}(E_\nu/E_{\mu,\mathrm{cool}})$


$(\Phi_{\nu_\alpha}/\Phi_{\nu_e})^{3+2\,\mathrm{MM}} / (\Phi_{\nu_\alpha}/\Phi_{\nu_e})^{3\,\nu}$
$\mathrm{Log}_{10}(E_\nu/E_{\mu,\mathrm{cool}})$


$(\Phi_{\nu_\mu}/\Phi_{\nu_\tau}+\Phi_{\nu_e})^{3+2\,\mathrm{MM}} / (\Phi_{\nu_\alpha}/\Phi_{\nu_\tau}+\Phi_{\nu_e})^{3\,\nu}$
$E_{\mu,0} = 1\ \mathrm{TeV}$
E_ν [GeV]

Outlook

- Important to test anomalies in new regimes in order to test correct framework and parameter space
- IceCube: good sensitivity to additional neutrinos at $\sim eV$ scale
- a lot of model dependence
- specific, very constrained 3+2 minimal model

  one additional mixing angles contributes everywhere

  good sensitivity at energies from 100 GeV to 10 TeV

  use energy and angular distribution

  some sensitivity at energies from 10GeV to 100GeV

  constant contribution: use high statistics DeepCore data

  good sensitivity at high energies

  flavor ratios of neutrinos from astrophysical sources

  precision measurements of active flavor oscillations provide additional constraints

Backup

3+2 Minimal Model

Mixing matrix:

$$U = \begin{pmatrix} U_{aa} & U_{as} \\ U_{sa} & U_{ss} \end{pmatrix},$$

$$U_{aa} \quad = U_{PMNS} \begin{pmatrix} 1 & 0 \\ 0 & H \end{pmatrix}, \; U_{as} \quad = iU_{PMNS} \begin{pmatrix} 0 \\ Hm_l^{1/2} R^\dagger M_h^{-1/2} \end{pmatrix}$$

$$U_{sa} = i \left(0 \; \overline{H} M_h^{-1/2} R m_l^{1/2} \right), \; U_{ss} = \overline{H}.$$

$$H^{-2} = I + m_l^{1/2} R^\dagger M_h^{-1} R m_l^{1/2}. \qquad m_l \equiv Diag(m_2, m_3)$$

$$\overline{H}^{-2} = I + M_h^{-1/2} R m_l R^\dagger M_h^{-1/2}. \qquad M_h \equiv Diag(M_1, M_2)$$

$$R = \begin{pmatrix} \cos(\theta_{45} + i\gamma_{45}) & \sin(\theta_{45} + i\gamma_{45}) \\ -\sin(\theta_{45} + i\gamma_{45}) & \cos(\theta_{45} + i\gamma_{45}) \end{pmatrix}$$

$$S_j = \frac{N_J}{N_J^0}$$

Number of events with oscillations in j^{th} cos bin

Number of events without oscillations in j^{th} bin

$$N_j = 2\pi\rho_{ice} A_{IC} \langle R(E)\rangle t N_A \int_{\Delta_j \cos(\theta_z)} d\cos(\theta_z) \int_{100\ \mathrm{GeV}}^{400\ \mathrm{TeV}} dE\ \left(\Phi_\mu(E,\cos) P_{\mu\mu}(E,\cos) e^{-N_A \sigma_{tot}(E) \int_0^{2R_\odot \cos} dl \rho(\cos,l)}\right)$$
$$+\ \text{antineutrinos}$$

Mean inelasticity

$$\langle R(E)\rangle = \left\langle \frac{1}{b} \ln\left(\frac{a + bE(1-\langle y\rangle)}{a + b400\ \mathrm{GeV}}\right)\right\rangle$$

0.00033 1/m

0.24 GeV/m

- Test sensitivity of IceCube data to sterile neutrino mixing

$$N_j^{fit}(C,\tau,\Delta m_{51}^2,\Delta m_{41}^2,\theta_{45},\gamma_{45}) = \underbrace{C}_{\text{Normalization}}(1+\underbrace{\tau}_{\text{Zenith angle tilt parameter}}(\cos(\theta_j)+0.5))N_j^{MC}S_j(\Delta m_{51}^2,\Delta m_{41}^2,\theta_{45},\gamma_{45})$$

- Set C, τ by minimizing fit

$$\chi^2(C,\tau,\Delta m_{51}^2,\Delta m_{41}^2,\theta_{45},\gamma_{45}) = \sum_j \frac{\left(N_j^{data} - N_j^{fit}(C,\tau,\Delta m_{51}^2,\Delta m_{41}^2,\theta_{45},\gamma_{45})\right)^2}{\left(\sigma_j^{data}\right)^2}$$